01 Jan 2002

ESD Currents and Fields on the VCP and the HCP Modeled using Quasi-Static Approximations

David Pommerenke
Missouri University of Science and Technology, davidjp@mst.edu

Wang Kai

Thomas Van Doren
Missouri University of Science and Technology

Recommended Citation

D. Pommerenke et al., "ESD Currents and Fields on the VCP and the HCP Modeled using Quasi-Static Approximations," *Proceedings of the IEEE International Symposium on Electromagnetic Compatibility, 2002. EMC 2002*, Institute of Electrical and Electronics Engineers (IEEE), Jan 2002.
The definitive version is available at https://doi.org/10.1109/ISEMC.2002.1032452

ESD Currents and Fields on the VCP and the HCP Modeled Using Quasi-static Approximations

David J. Pommerenke, Thomas P. Van Doren, Wang Kai

Electromagnetic Compatibility Laboratory

Electrical and Computer Engineering Department

University of Missouri - Rolla

Rolla, MO, USA 65409-0040

davidjp@ece.umr.edu, vandoren@umr.edu, kwrff@umr.edu

Abstract

The horizontal coupling plane (HCP) and the vertical coupling plane (VCP) are essential elements of the standardized electrostatic discharge (ESD) test. They are used for testing the robustness of equipment against indirect (nearby) discharges. This article analyzed the current and the fields on the HCP and the VCP using plane wave, transmission line, quasi-static theory. The objective is to illustrate the dominating physical processes on these planes. The work is based on measurements of the transient currents and fields using broadband sensors.

Keywords

Electrostatic discharge, transient fields, susceptibility

INTRODUCTION

Discharges to the HCP and the VCP test the robustness against indirect (nearby) discharges. The test setup was modified by the standard setting body IEC TC77b from a vertical simulator position for discharges to the HCP to discharges to the edge using a horizontal simulator position. Reference [1] analyzes the effect of this change.

Although previous research has shown field data [1,2], no publications are known to the authors that explain the overall physical picture of the processes on these planes. This is the objective of this article.

First the fields on the HCP are analyzed for discharges to the VCP. Second, the processes on the HCP are analyzed for discharges to the edge of the HCP.

Analysis of the Vertical Coupling Plane (VCP)

A typical test setup that uses the VCP is shown in Fig. 1.

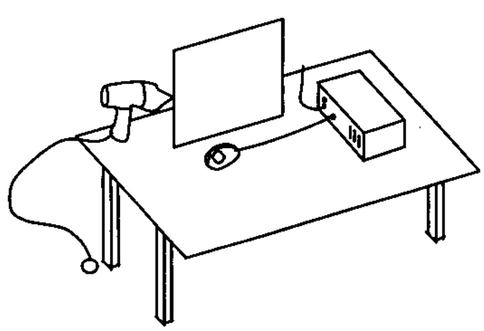

Figure 1: *Typical test setup for discharges to the VCP. The signal couples into a mouse cable.*

1.1 Injected current

The current is injected into the VCP, Fig. 2.

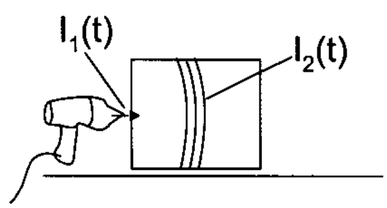

Figure 2: *Model used to describe the VCP current.*

At first, two questions need to be answered: How is I_1 related to the current seen during a calibration of the simulator, and how much of that current will propagate along the VCP shown as current I_2 in Fig. 2. It is indicated in Fig. 3 that the current into the edge of the VCP is sufficiently similar to the current seen during a calibration to allow using the calibration current as the injected current.

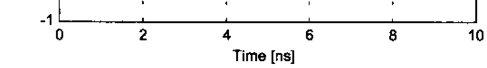

Figure 3: *Current into the VCP compared to the current seen while discharging into a large groundplane, contact mode 1kV.*

Next it needs to be shown that the injected current will propagate using the VCP as a short transmission line. To verify this, a VCP of 1 m length was setup and terminated in its characteristic impedance. Field sensors were placed on the HCP to measure the field strength along the VCP. The top view of the setup is shown in Fig. 4.

0-7803-7264-6/02/$17.00 © 2002 IEEE

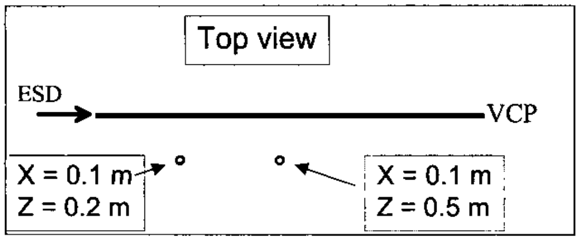

Figure 4: *Field sensor positions relative to the VCP and the injection point to show that a wave is propagating along the VCP. A terminated 1 m long VCP was used.*

The measured fields are shown in Fig. 5.

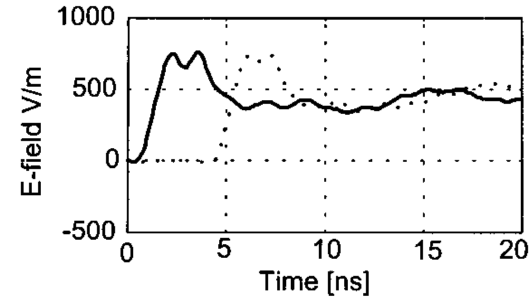

Fig. 5: *Fields as measured at the locations z = 0.2 m and 0.5 m shown in Fig. 4.*

The data shows that within 0.1 m of the discharge edge, a wave has been established that travels along the VCP. The differences in the wave shape relative to Fig. 3 are also visible. Part of the initial current pulse is injected into the VCP but not injected into the traveling wave. It returns as displacement current directly to the simulator (no net charge returns to the simulator via that path, so the displacement current return acts as a low-pass filter for the current).

If,

- the injected current would be identical to the current seen in a calibration of an ESD simulator, and
- if all current would travel along the VCP,

then the voltage on the VCP could be calculated by:

$$V(t) = Z_{VCP} \cdot I_{cal}(t)$$

It is also possible to obtain the voltage from the measured E-field (see next paragraphs for details). Both can be compared to test the overall accuracy of the injection model.

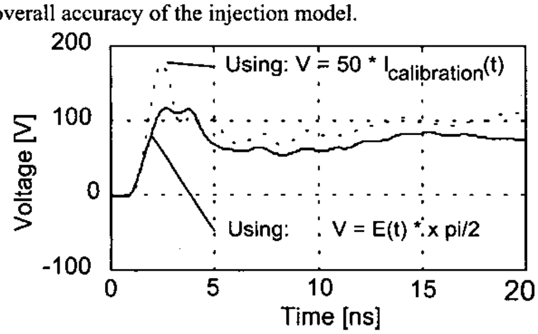

Figure 6: *Comparison of two methods to calculate the voltage on the VCP (assuming infinitely long VCP, or terminated VCP).*

1.2 Field structure - transmission line

The VCP over HCP structure is a transmission line. The characteristic impedance was determined numerically by placing unknown line charges inside the metal and solving for the known potentials on the surface. Analytical solutions for slot-lines would work equally well. The field structure around the VCP is schematically shown in Fig. 7.

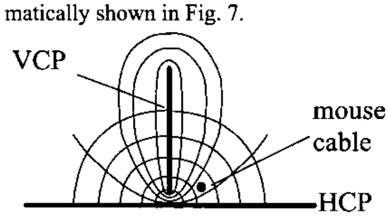

Figure 7: *Schematic drawing of the electric and magnetic field structure around the VCP/HCP pair seen as a transmission line.*

Of course, this model is only valid for the first few nanoseconds as the wave will be reflected at the end of the VCP. For later times a static field will dominate (high field impedance), while the traveling waves will maintain a 377 Ohm field for the first few nanoseconds. During this initial time period, the magnetic field and the electric field derivatives will reach their highest values. The severity of the ESD pulse is a maximum when the field derivatives are a maximum. The impedance of the VCP-HCP transmission line is shown in Fig. 8.

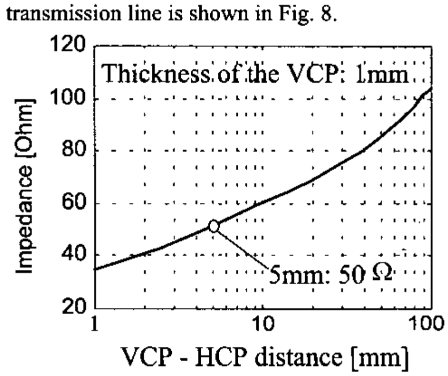

Figure 8: *Impedance of the VCP-HCP transmission line as a function of the height above the HCP.*

To stay within the concept of this article of providing simple approximations of the fields on the HCP, it is assumed that the electric field lines between the VCP and the HCP form circular arcs equal to ¼ the circumference. As a consequence, the electric field (which equals the charge density divided by ε_o) will decrease by $1/x$, if x is the distance between the VCP and the point of observation on the HCP. To verify this assumption the charge density was numerically calculated and multiplied by x.

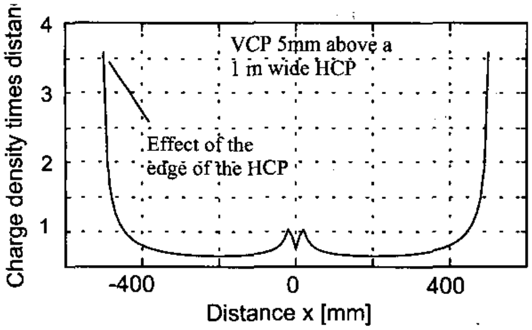

Figure 9: *Charge density multiplied by the distance in x- direction (perpendicular to the VCP, x=0 is directly beneath the VCP).*

For locations that are between 50 and 300 mm to the side of the VCP (direction x) the product of the charge density and the distance is nearly flat, i.e., the charge density decreases by 1/x. This shows that the assumption of 1/4 circular arc length for the electric field lines holds quite well for that region. It allows a simple way to obtain the electric and the magnetic field intensities.

First the voltage difference between the VCP and the HCP is needed. It is approximated by:

$$V(t) = I_{ESD}(t) \cdot Z_{VCP}$$

Here I_{ESD} equals the current that is measured if the ESD simulator is discharged into a large ground plane. The peak current is about 3.75 A/kV. Z_{VCP} is the impedance of the VCP-HCP transmission line structure.

From the knowledge of the voltage, the electric field on the HCP is obtained, simply by dividing the voltage by the length of the 1/4 circular arc of radius x:

$$E(t,x) = \pi \ V(t)/(0.5 \ \cdot x)$$

The magnetic field is obtained by assuming that the wave is a plane wave. This assumption has been verified by measurements, Fig. 10.

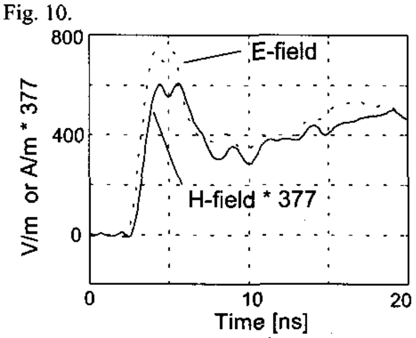

Figure 10: *Electric and magnetic field on the HCP.*

After the initial wave has been reflected at the end of the VCP, all waves that travel along the VCP need to be taken into account to determine the wave impedance.

1.3 Coupled transmission line model

So far the current and voltage on the VCP and the electric and the magnetic field on the HCP have been estimated. In the next step, the finite length of the VCP is taken into account and a mouse cable is added parallel to the VCP as a susceptible circuit. The VCP-HCP transmission line and the mouse cable-HCP transmission line can be modeled as two coupled transmission lines.

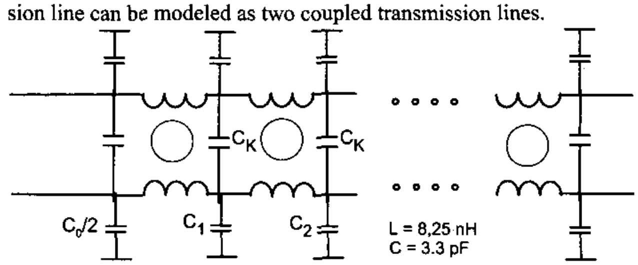

Figure 11: *Two coupled transmission line model to calculate the coupling between the VCP-transmission line and the mouse cable. The mutual capacitances have been derived numerically.*

As the mutual inductance and the mutual capacitances are in a fixed ratio, only one of them needs to be determined. For homogeneous media their relationship is given by:

$$\sqrt{Z_1 \, Z_2} \ = \ M / C_k ;$$

where Z_1 and Z_2 are the characteristic impedances of the mouse cable-HCP and the VCP-HCP transmission lines.

1.4 ESD simulator model

As a final step, the injected current needs to be modeled. Two different methods have been used: 1. modeling the ESD simulator as a current source having a 330 Ohm source resistance; and, 2. modeling the current waveform as given by the standard. The results do not differ significantly with respect to the overall accuracy of this simplified approach.

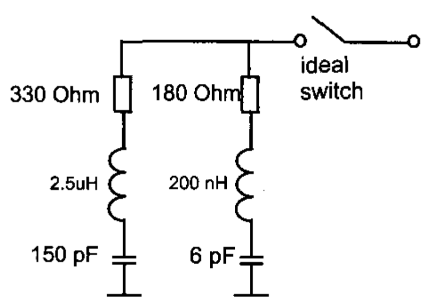

Figure 12: *Equivalent circuit used to model the injected current.*

The current of the model compares reasonably well to the measured calibration current as shown in Fig. 13.

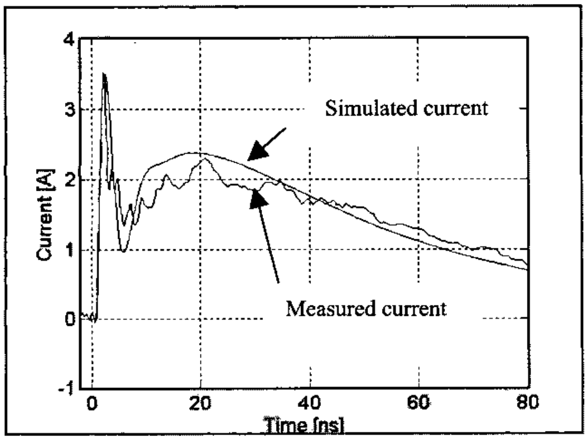

Fig. 13: *Simulated and measured ESD current, 1 kV charging voltage in contact mode.*

Now the ESD simulator can be attached to the coupled line model. This allows the induced voltage to be simulated.

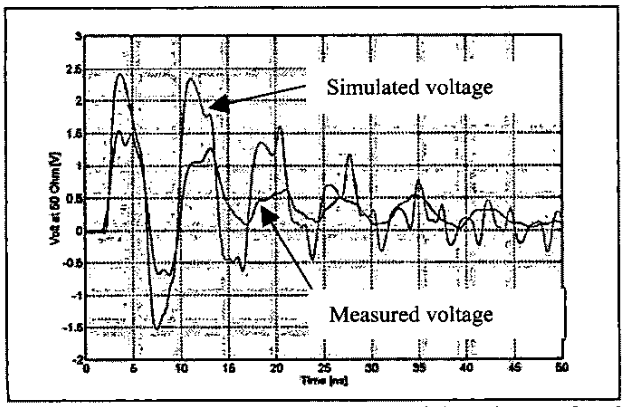

Fig. 14: *Simulated and measured result of the voltage induced into a mouse cable at a 50 Ohm load.*

The simulation matches the measurement in its main characteristics. The simulated data show larger peak values. This is most likely due to the assumption that all of the current is injected into the VCP as a traveling wave. The data displayed in Fig. 3 indicated that this assumption is only partialy true.
Nevertheless, the overall aim was not to show a detailed analysis (as this could be done e.g., in FDTD) but to illustrate the dominating physical processes using a simple model.

Analysis of the Horizontal Coupling Plane (HCP)

Using the HCP, discharges are done as follows. The equipment under test is placed at a distance of 0.1 m from the edge of the HCP. The ESD simulator is discharged in the contact mode to the edge of the HCP. The operator needs to hold the ESD simulator in the plane of the HCP. This situation is analyzed.

1.5 Measurement setup

Two different setups were used:

- Standard HCP (metallic plane 0.8 x 1.6m, 0.8 m above ground)
- Large HCP (2.4 m semicircle plane, 0.8 m above ground)

Data were measured using a battery powered TEK 3052 (5 GS/sec, 500 MHz, 9 bit) oscilloscope and self-made ground based E- and H-field sensors. The sensors have a flat frequency response from 2 MHz - 2 GHz (+/- 1.5 dB). The lower frequency roll-off was deconvoluted by using a mathematical model of their frequency response. This reduces the effect of the lower cut-off frequency on data for times later than 10 ns after the ESD. The deconvolution has been carefully checked against stepped wave signals in a stripline test structure to avoid overcorrecting, i.e., diverging for long times.

1.6 The general picture

The analysis of the HCP is not as simple as for the VCP. It is assumed that no equipment has been placed on the HCP. Such equipment under test could affect the fields. By using the simplified physical models described above, one can estimate the ESD fields equipment under test would experience if placed on the HCP.

The first nanoseconds

Upon discharge to the center of one edge of the HCP, two waves are launched:

- An edge wave. This propagates along the edge of the HCP.
- A surface wave: There are two waves one on the top and one on the bottom of the HCP. Both are of similar magnitude. They propagate on the surface as plane waves until they are reflected by the edges.

Later times

The waves will be reflected multiple times. Upon each reflection their magnitude is decreased. Of course, the total charge will stay the same. As there is less current flowing, the ratio of electric to magnetic field will increase, until more or less quasi-electrostatic conditions occur. A slow decay of the electric field is caused by the 1 MOhm grounding resistor that connects the HCP to the ground plane.

1.7 Detailed analysis

The first nanoseconds

The current that is injected into the edge of the HCP using a horizontal simulator position will create an edge wave and waves on the top and on the bottom of the HCP.

The field intensity for the edge wave will change only slightly as the wave travels along a transmission line formed by the edge of the HCP, the nearest walls (in the setup the walls where about 0.5m away) and the ground plane. The plane wave traveling across the surface of the HCP will produce a field strength that decreases by 1/r and a field impedance that is close to 377 Ohm, excluding the regions close to the edges.

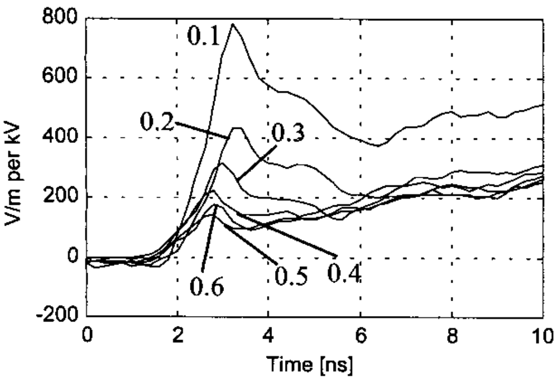

Fig. 15: *Early variation of the electric field with time at various distances in meters along the edge of the HCP from the point of the discharge. The electric field is normalized to the discharge voltage in kV. The discharge is applied perpendicular to the edge and in the plane of the HCP.*

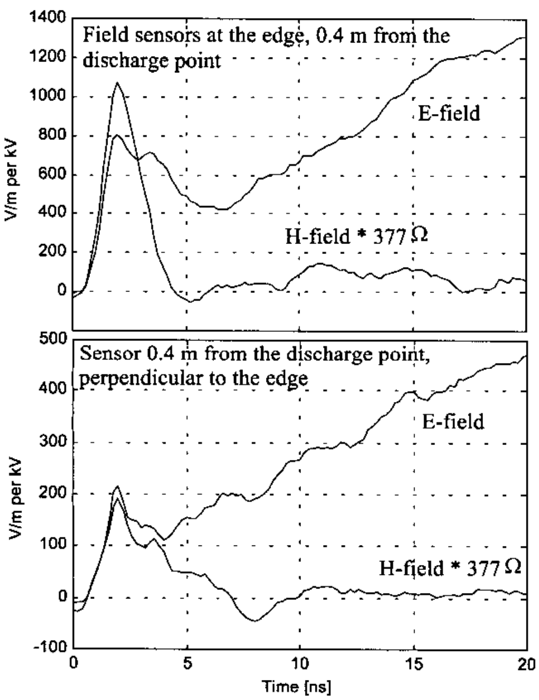

Fig. 16: *Measured electric and magnetic fields on the HCP 0.4 m from the discharge point. Top: at the edge, alpha=0 deg., Bottom: 0.4 m into the plane, alpha = 90 deg.*

Current density

For the VCP, it was a reasonable assumption that all of the current would be injected into the VCP. This is also true for the HCP, but a large part of the current will flow along the edge. From the measured magnetic field it is possible to obtain the injected current over a certain region of the HCP. The current density does not change significantly between $\alpha = 45$ degrees to 135 deg.

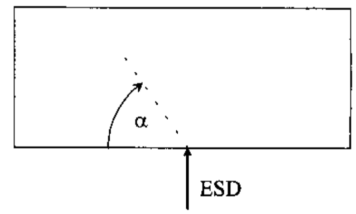

Fig. 17: *Geometry for integrating the current density on the HCP.*

The magnetic field at alpha = 90 deg is about 0.6 A/m per kV at a distance of 0.4 m from the discharge point, Fig. 16. Assuming the current density is constant, a total current of 0.34 A is flowing between 45-135 deg. If we, just as a test, assume that the same current flows on the bottom and on the top surfaces between 0-45 deg and 135-180 deg, then the total current would be 0.34 * 4 = 1.36 A. Based on measurements, the total current is about 3.75 A, thus the majority of the current is flowing along the edges, outside the 45-135 deg. range.

Measurements on the large HCP (2.4 m semicircle) showed that the current at 0.2 m and 0.4 m radius from the discharge point follows a square-root function of the distance along the semicircular arc. This relationship cannot hold up for large distances from the discharge point, as the edge wave will not decrease (it even reached a constant value after about 1.5m on the 2.5m semicircle HCP) as rapidly as the wave that travels on the HCP (1/r dependence).

Late part of the waveform

The late part of the waveform exposes the equipment under test to a high impedance field that is slowly changing. The author has seen keyboards that are sensitive to this part of the waveform. A way to identify this is to use a high impedance (MOhm) ground strap on the ESD simulator. With such a modification, the simulator will still inject most of its initial impulse, but will not inject the later part of the current waveform. Thus, the fast wave fronts stay unchanged on the HCP, but the high impedance field will not be established.

After the fast waves have settled, the equivalent circuit shown in Fig. 18 is valid.

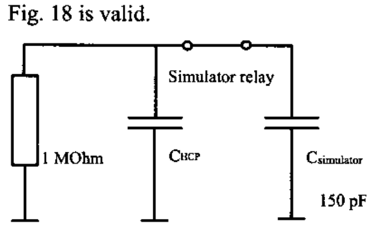

Fig. 18: *Equivalent circuit for determining the voltage on the HCP valid after about 20 ns involves the simulator capacitance and the capacitance between the HCP and the ground plane.*

The problem with this equivalent circuit is that the status of the relay is unknown. The current may not be sufficient to sustain an arc in the relay. Additional grounded equipment under test would be modeled by an additional capacitance. The injected charge is distributed onto the simulator and the HCP capacitance allowing the determination of the maximum voltage to which the HCP can charge. The electric field is nearly constant throughout the HCP with the exception of the edges (Fig. 19).

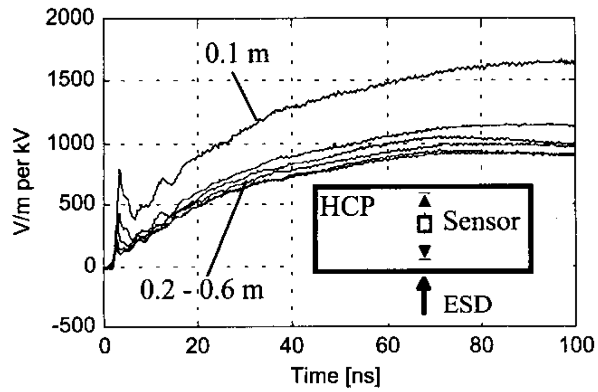

Fig. 19: *Measured electric field on the HCP as a function of distance from the discharge point along a line perpendicular to the edge. The data is shown in V/m per kV charging voltage (Minizap ESD simulator)*

A static electric field value is reached after about 80 ns. It is independent of the position on the HCP, excluding the proximity to the edges that is already visible at 0.1 m distance.

CONCLUSIONS

Using transmission line theory, plane wave theory and quasi-static methods the dominating physical processes on the horizontal coupling plane and the vertical coupling plane as a result of ESD are described, mainly to visualize the processes. Based on these results, a simulation of the fields and the coupling to cables is provided.

REFERENCES

S. Frei, D. Pommerenke, *'Fields on the horizontal coupling plane excited by direct ESD and discharges to the vertical coupling plane'*, Jour. of Electrostatics 44 (1998), pp.177-190

Iwata, Y. Akao, *'Characteristic of E-field near indirect ESD-events'*, IEEE Int. Sym. EMC, Dallas, TX, 1993